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TRIAXIAL TESTING OF BRITTLE SANDSTONE USING A MULTIPLE FAILURE STATE METHOD

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TRIAXIAL TESTING OF BRITTLE SANDSTONE USING A MULTIPLE FAILURE STATE METHOD

by

P. Cain*, C.M.K. Yuen**, G. LeBel**, A. Crawford*** and D. Lau***

ABSTRACT

The first phase of a recent research programme undertaken to investigate sandstone/methane outbursts in coal bearing rocks required the use of a sandstone reference material in the development and trial of the testing procedures to be used. This was because the number of samples of outburst-prone rocks from the affected mine was limited. Thus another goal of the first phase was to determine a triaxial testing method for characterising rock properties that minimised the number of samples required. The ISRM Multiple Failure State Method is attractive in this regard because an approximate strength envelope can be determined from a single specimen.

In this test programme, however, the brittle nature of the reference material made control of failure by monitoring axial strain (the ISRM method) impossible; samples always failed at the first, low or zero confinement, stage. An alternative method of detecting imminent failure in the specimen was developed and applied, yielding results almost identical to those obtained by conventional single state testing.

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*Research Scientist, Cape Breton Coal Research Laboratory, CRL, CANMET, Energy, Mines and Resources Canada, Sydney.

**Golder Associates Eastern Canada, 3151 Wharton Way, Mississauga, Ontario, L4X 2B6, Canada.

***Department of Civil Engineering, University of Toronto, Ontario, M5S 1A4, Canada.

ESSAI TRIAXIAL SUR LES GRÈS CASSANTS EN UTILISANT LA MÉTHODE DE L'ÉTAT DE FRAGMENTATION MULTIPLE

par

P. CAIN*, C.M.K. YUEN**, G. LEBEL**, A. CRAWFORD*** ET D. LAU***

RÉSUMÉ

La première étape d'un récent programme de recherche entrepris pour étudier les explosions de grès/méthane dans les roches porteuses de charbon, a requis l'utilisation d'un matériel de référence en grès dans le développement et l'essai des diverses étapes des tests qui seront utilisés. En effet, le nombre d'échantillons de roches prédisposées aux explosions et provenant de la zone affectée, était limité. De plus, un deuxième but de cette étape consistait à déterminer une méthode d'essai triaxial permettant de caractériser les propriétés des roches, de façon à réduire le nombre d'échantillons requis. La méthode de fragmentation multiple, dite ISRM, est intéressante puisqu'elle permet de déterminer à partir d'un seul échantillon une enveloppe de force approximative.

Cependant, dans ce programme de test, la nature cassante du matériel de référence a contrôlé les fragmentations en dirigeant les tensions axiales, ce qui a rendu la méthode ISBM inopérente; ainsi les échantillons flanchent toujours au premier, au bas ou à zéro de confinement. Une méthode alternative de détection des fragmentations imminentes dans les échantillons a été appliquée, accomodant les résultats de façon presque identique à ceux obtenus à partir des tests d'état simple conventionnels.

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*Chercheur scientifique, Laboratoire de recherche sur le charbon du Cap-Breton, LRC, CANMET, Énergie, Mines et Ressources Canada, Sydney.

**Golder Associates Eastern Canada, 3151 Wharton Way, Mississauga, Ontario, L4X 2B6, Canada.

***Département de Génie civil, Université de Toronto, Ontario, M5S 1A4, Canada.

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INTRODUCTION

In an effort to determine conditions leading to the occurrence of sandstone/methane outbursts at a Canadian coal mine, CANMET-CRL Sydney, Energy, Mines and Resources Canada, let a contract (1) for the simulation of such events under laboratory conditions using specimens of the burst-prone strata from the affected mine. Because of the limited availability of such specimens, it was specified that the development and trial of the simulation procedures were to be carried out on a sandstone reference material.

Conventional single stage triaxial tests, in which a confining pressure is set and axial load applied to failure, require a large number of samples to produce a complete strength envelope. In the ISRM Multiple Failure State tests (2,3) imminent failure of the specimen (defined here as a state in the specimen where growth and propagation of microcracks has been initiated but the specimen is still stable) was recognised by a flattening of the stress/axial strain curve, and the confinement increased to the next level before total failure. Thus a complete strength envelope can be obtained from one specimen. This strength envelope generally lies between the yield envelope and the peak strength envelope. It is conceivable that using the yield stress as the imminent failure criterion would seriously underestimate the peak strength. It is also recognised that repeated cycling of the specimen towards failure could result in the reduction of the peak strengths obtained at the upper range of confining pressures used. For this reason, a calibration between the strength envelope obtained from single stage tests and that obtained from multiple state testing was sought.

The sandstone reference material selected for this phase of testing was a light grey, medium grained, homogeneous sandstone. It was obtained from a stone supplier in the form of a 700 mm x 700 mm x 76 mm slab. Basic mechanical properties presented in Table 1 were obtained from 54 mm diameter samples (sub-cored from the slabs) end dressed to the appropriate length in accordance with standards specified by the International Society for Rock Mechanics (ISRM) (4).

Conventional single stage triaxial testing of the reference material was accomplished satisfactorily in accordance with ISRM standard testing procedures. However when multiple failure state testing was tried, using axial strain control, it was extremely difficult to prevent specimen failure

Table 1 - Basic mechanical properties of the reference sandstone

Description	- homogeneous, light grey, medium grained sandstone
Dry Density	- 2.189 g/cc
Porosity	- 19%
Permeability	- nitrogen gas

Confining Pressure (MPa)	K* (sq/min)	k** (cm/sec)
5	7.96×10^{-8}	5.22×10^{-6}
10	8.06×10^{-8}	5.24×10^{-6}

Uniaxial Compressive Strength: 43.27 MPa

Tensile Strength (Brazilian): 4.31 MPa

* Intrinsic permeability

** Coefficient of permeability

at the zero or low confining pressure stages. Examination of various inter-relationships between stresses and strains determined from previously tested specimens identified the relationship between volumetric strain and axial strain as being a suitable alternative criterion for the detection of imminent failure in the multiple failure state tests. The laboratory testing procedures are described below.

LABORATORY TESTING

SAMPLE PREPARATION

Right circular cylinders of the reference sandstone were sub-cored from the slab using a laboratory core drill and end dressed in an automatic grinder. All samples were 54 mm in diameter and 125 mm in length, an aspect ratio of 2.34:1. All the preparation was in accordance with ISRM standards (4).

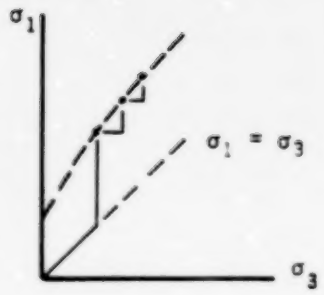
Resistance wire strain gauges were used to monitor axial and circumferential strains from which the volumetric strains were deduced. Two sets of diametrically opposed gauges were mounted at the mid-height of the specimen. Each set consisted of two gauges; one parallel and one perpendicular to the axis of the specimen.

SINGLE STATE TESTING

A Hoek triaxial cell loaded in a 1.2 MN Louis Small C-CP250 test frame was used, with a loading rate that ensured failure within 300 seconds. Triaxial cell pressure was monitored to ±1% using a pressure transducer. A total of ten tests were conducted at confining pressures of 5, 10, 20 and 30 MPa. After failure of each specimen, testing was continued to determine the residual strength envelope.

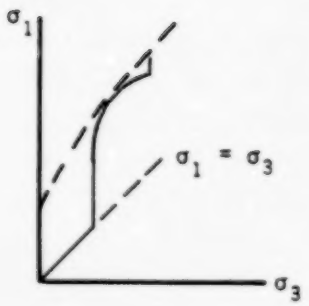
MULTISTAGE TESTING (ISRM METHOD)

ISRM standards (2,3) define two types of multistage testing; the multiple failure state (type II) test and the continuous failure state (type III) test. The stress paths followed by the specimens during these test procedures are illustrated in Figure 1. Using the same test frame and following the recommended stress paths, both procedures were tried on



A) ISRM Multiple Failure State Test

1. Hydrostatic loading.
2. Axial loading at constant strain rate.
3. Imminent failure detected.
4. Confining pressure increased in one step.
5. Steps 2, 3 and 4 repeated n times.
6. On nth stage axial loading continued to failure.



B) ISRM Continuous Failure State Test

1. Hydrostatic loading.
2. Axial loading at a constant rate until imminent failure detected.
3. Confining pressure continuously increased to prevent failure.
4. At a chosen point, confining pressure kept constant and axial loading maintained to failure.

Figure 1 - Stress paths followed by specimens during ISRM multistage testing

specimens of the reference sandstone. In all attempts, however, it was found impossible to control the failure process using the stress/axial strain response as the failure criterion because of the near linear elastic response of the specimens at zero and low confining pressures (Figure 2).

VOLUMETRIC STRAIN AS AN ALTERNATIVE IMMINENT FAILURE CRITERION

The difficulties in applying the ISRM standard multistage testing methods to produce acceptable results for the reference material required an alternative approach to the detection of imminent failure. Examination of the stress/strain and strain/strain relationships from previously tested specimens, one in uniaxial compression and one in triaxial compression (Figures 3 and 4) indicated that the point at which the volumetric strain ($\Delta v/v$) returned to zero on the $\Delta v/v$ versus ε_a plot appeared to be a more suitable criterion for imminent failure. The volumetric strain, $\varepsilon_v = \Delta v/v$, was derived from the axial (ε_a) and lateral (ε_l) strains using the following formula:

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_l$$

The stress level at which ε_v returns to zero is about 95% of the peak strength in both the cases illustrated. It therefore appeared that the adoption of this relationship as a criteria of imminent failure would give acceptable values in the determination of the peak strength envelope.

MODIFIED MULTISTAGE TESTING

In order to verify the practicability and validity of the ε_v criterion of imminent failure, two additional tests were carried out on specimens of the reference sandstone at standard ISRM loading rates using the following procedure:

STAGE 1 ($\sigma_3 = 0$ MPa)
- increase σ_1 until the volumetric strain returns to zero.
- reduce σ_1 to 0 MPa.
- record permanent deformation (if any).

STAGE 2 ($\sigma_3 = 10$ MPa)
- increase σ_1 and σ_3 to 10 MPa simultaneously at the same loading rate.

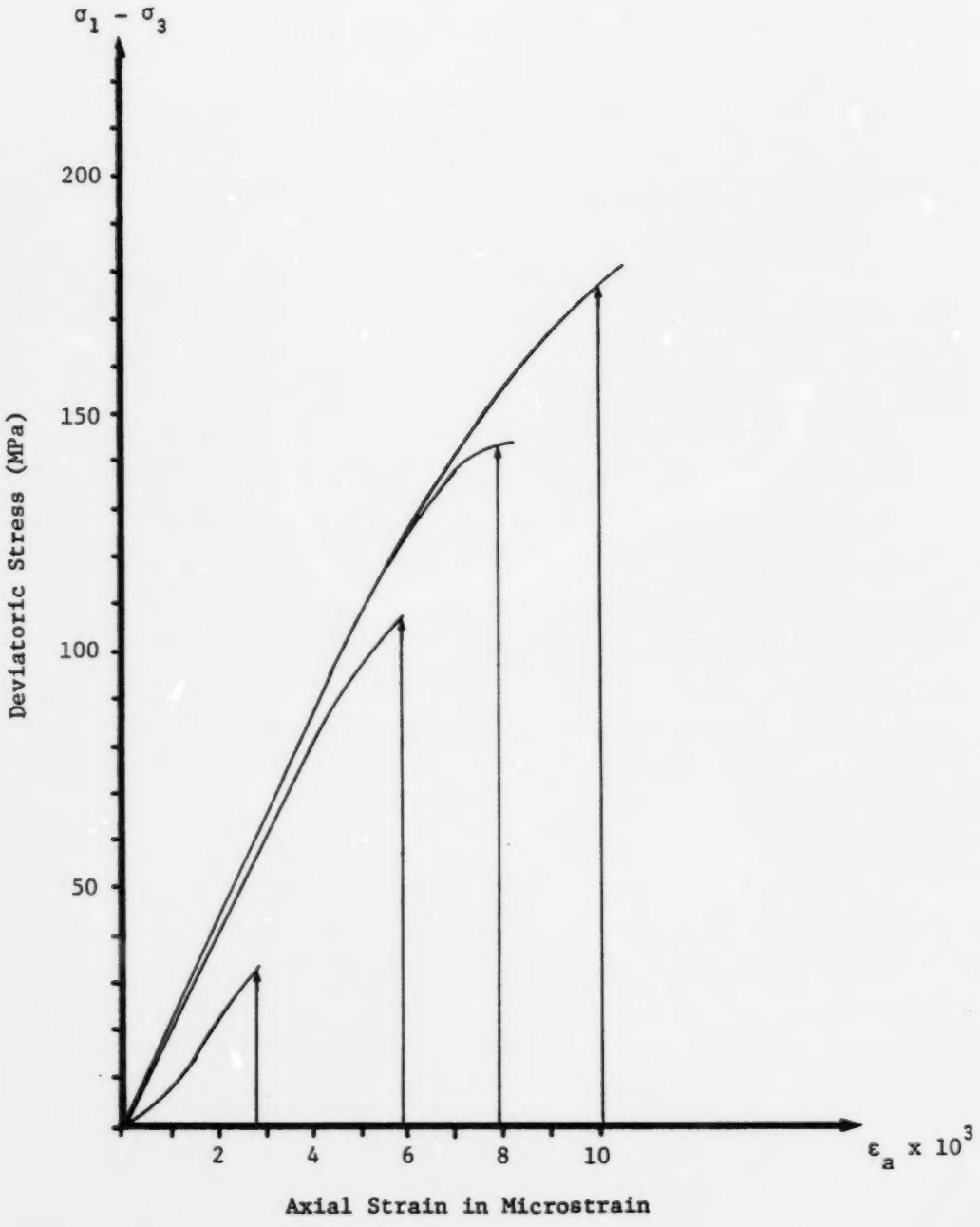


Figure 2 - Stress/strain curves for the reference sandstone (arrows indicate zero volumetric strain)

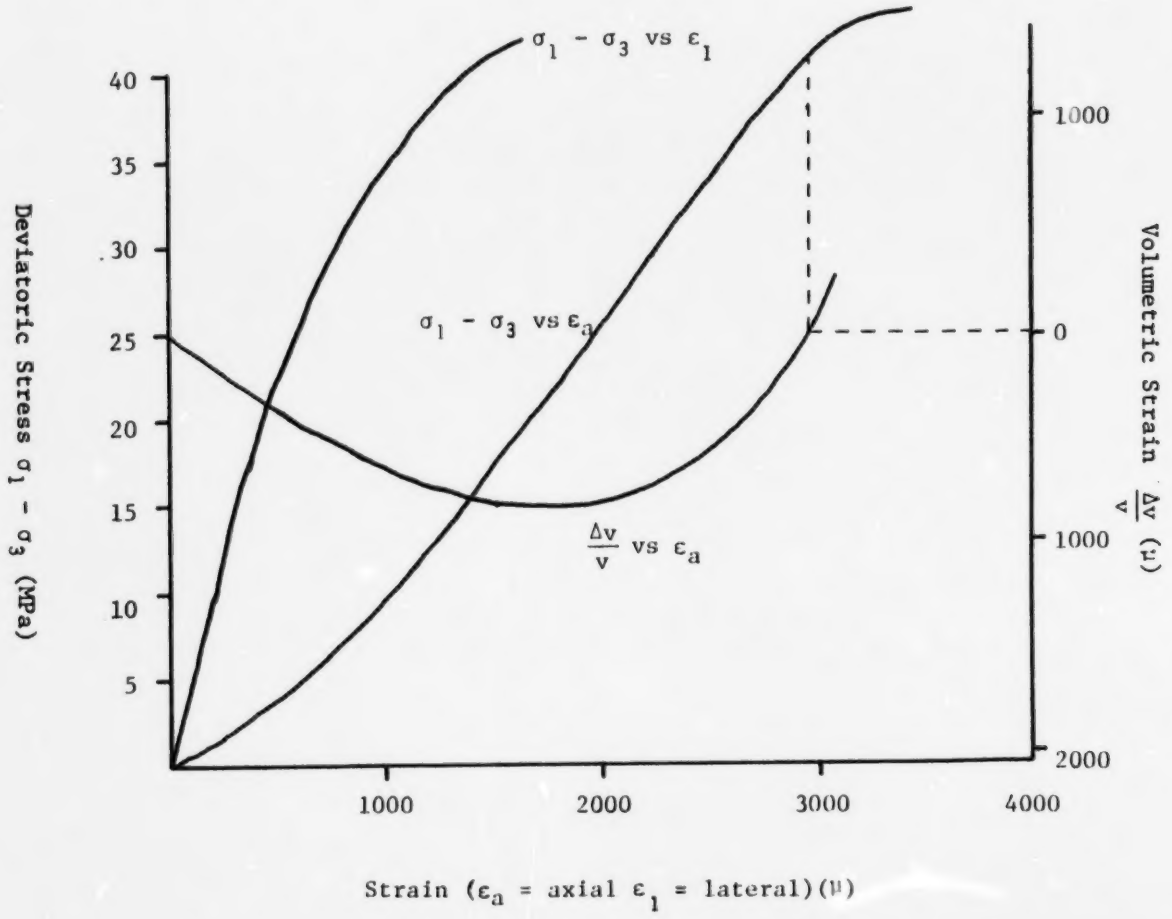


Figure 3 - Stress/strain and strain/strain relationships for a sample of reference sandstone tested uniaxially

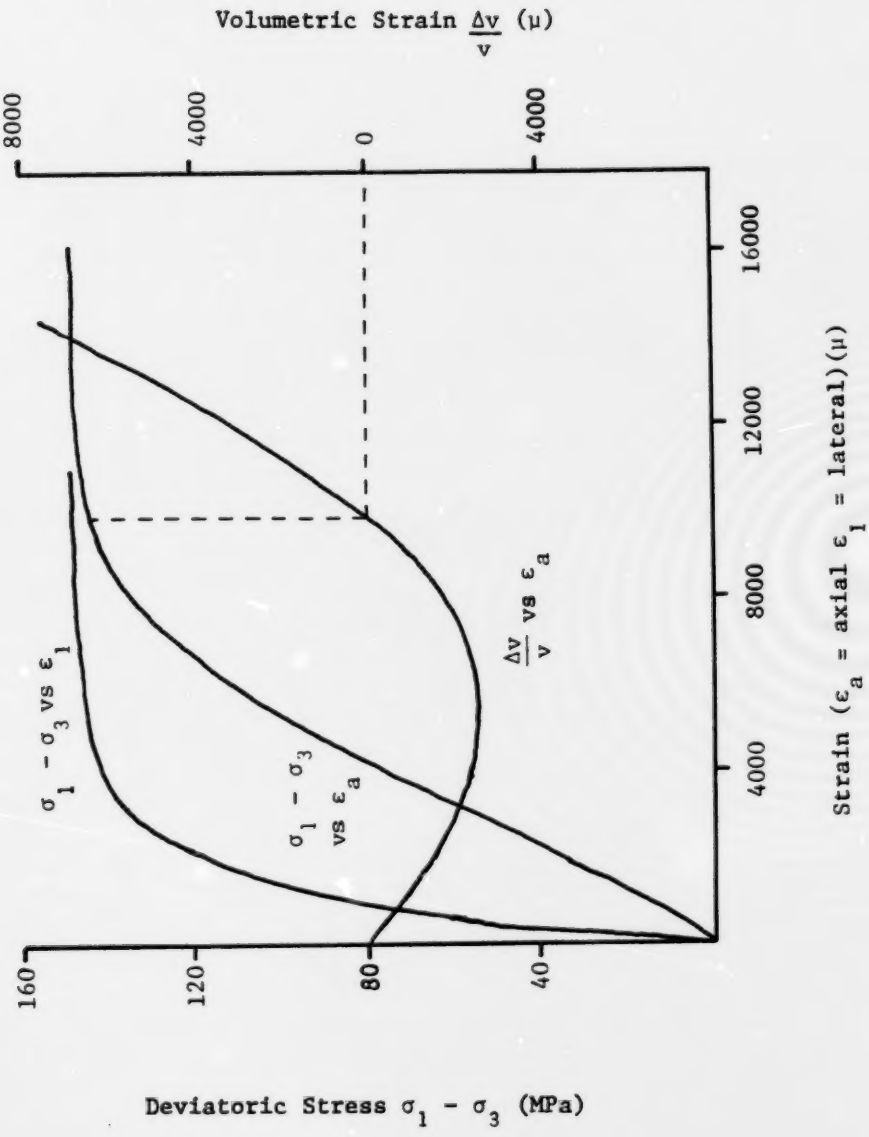


Figure 4 - Stress/strain and strain/strain relationships for a sample of reference sandstone tested triaxially

- zero all strain gauges.
- maintain σ_3 while increasing σ_1 until $\Delta v/v$ returns to zero.
- reduce σ_1 to 10 MPa
- record permanent deformation (if any)

STAGE 3 (σ_3 = 20 MPa)

STAGE 4 (σ_3 = 30 MPa)

- repeat steps of Stage 2 with initial values of σ_1 and σ_3 at 20 MPa and 30 MPa respectively.

The resulting stress paths are shown in Figure 5. At the final stage of testing, σ_3 was kept constant whilst σ_1 was increased until gross failure occurred.

RESULTS

SINGLE STATE TESTING

A summary of the single state testing results is given in Table 2. The peak and residual strength curves, plotted in the form σ_1 versus σ_3, are shown in Figure 6. The tensile strength values used to complete the peak strength envelope are those obtained during the preliminary characterisation of the reference material (Table 1). The most common mode of failure was along a single shear plane; 67° from the horizontal at low confining pressure, 62° from the horizontal at confining pressures above 20 MPa.

MULTISTAGE TESTING (ISRM STANDARD)

No results were obtained from this testing method for the reasons outlined above.

MODIFIED MULTISTAGE TESTING

The results obtained from the two tests conducted using the modified test method are summarised in Table 3. Figure 7 compares the peak strength envelope obtained using the modified method to that obtained using conventional single state triaxial testing methods described earlier.

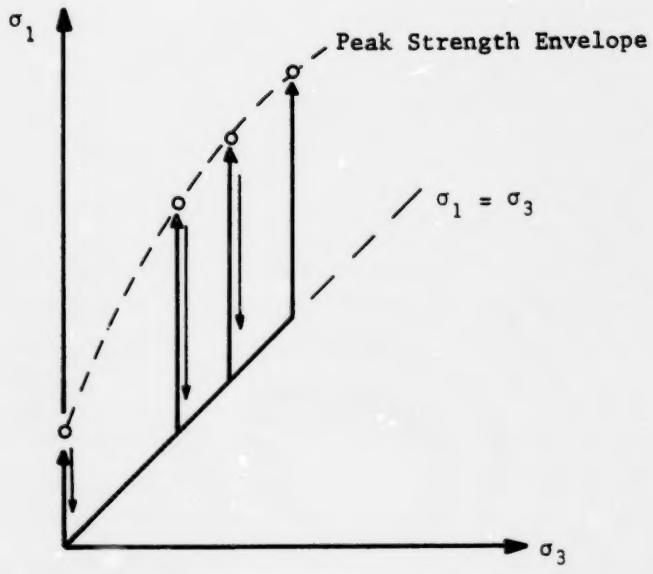


Figure 5 - Stress path followed by the sample during the modified testing procedure

Table 2 - Summary of single stage triaxial test results

Test	Initial Stress Level (MPa)		Stress Level at Failure (MPa)		Observed Failure Mode	Remarks
	σ_3	σ_1	σ_3	σ_1		
1	5	5	5	99.8	S,AS	Shear along diagonal
2	10	10	10	114.7		
3	10	10	10	97.2		
4	10	10	10	124.5	S,C,H	Shear along diagonal
5	10	10	10	122.5		
6	20	20	20	167.2	S,C,H	Shear at 62°
7	20	20	20	169.2		
8	30	30	30	204.2	S	
9	30	30	30	188.6	S	Shear at 62°
10	30	30	30	190.6	S	Shear at 62°

Mode of Failure - AS: Axial Splitting
C: Conjugate Planes
H: Horizontal
S: Shear

Table 3 - Peak axial stresses determined using the $\Delta v/v$ imminent failure criterion

σ_3 (MPa)	Peak Axial Stress (MPa)	
	Sample A	Sample B
0	33.4	34
10	117	112
20	164	164
30	203	Creep Failure

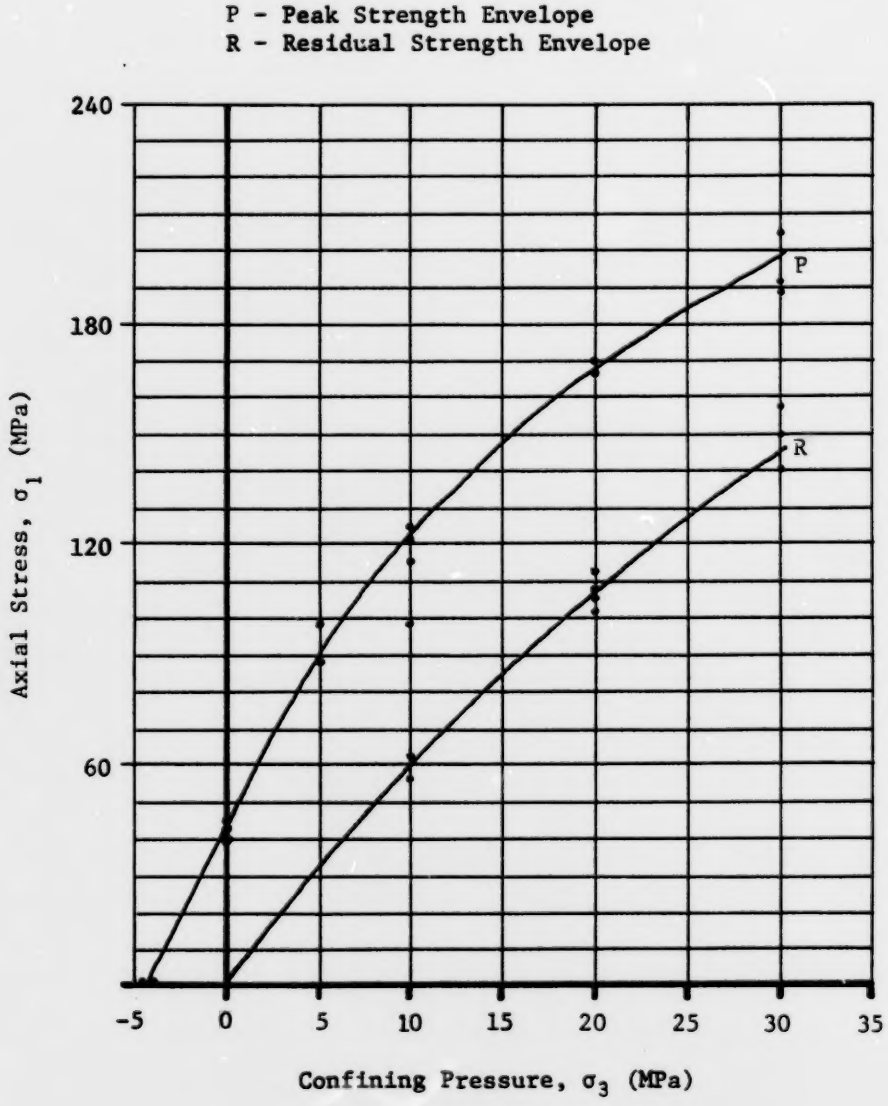


Figure 6 - Peak and residual strength envelopes obtained from conventional ISRM single stage testing of the reference sandstone

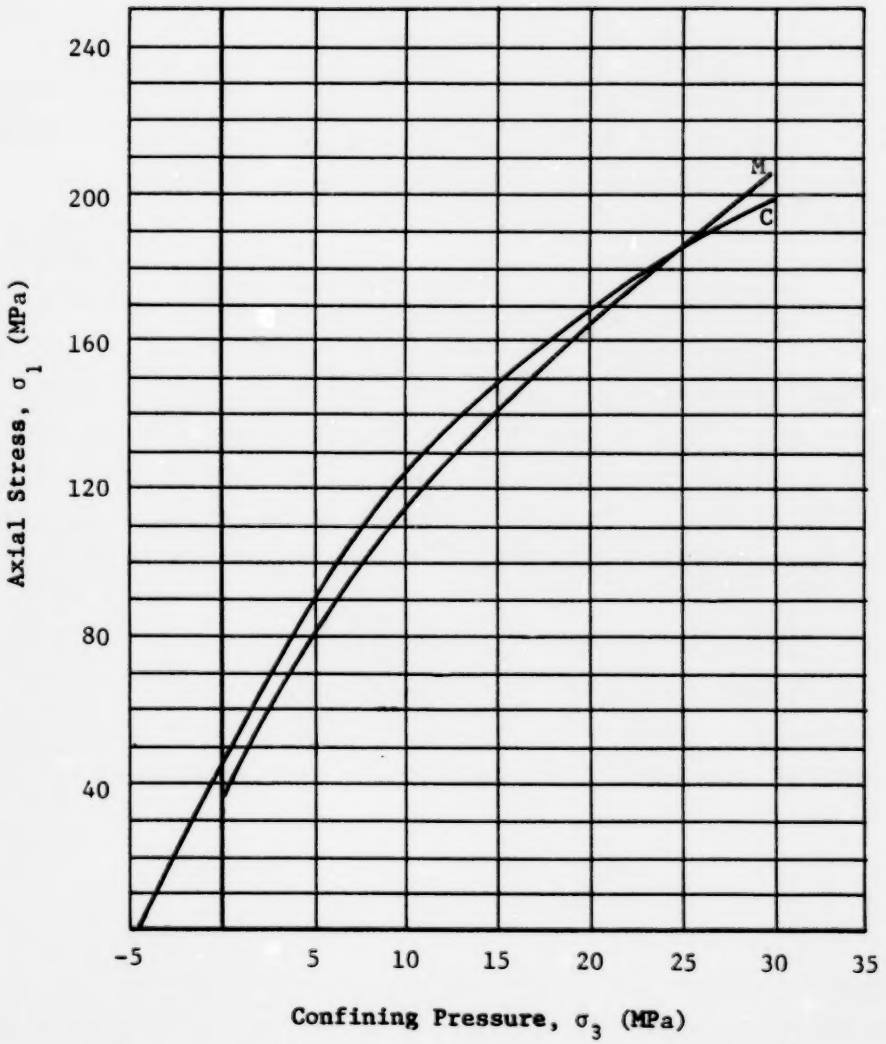


Figure 7 - Comparison of conventionally obtained peak strength envelope (C) with that obtained using the modified test method (M)

DISCUSSION AND CONCLUSIONS

The results of the tests described above show clearly that the modified test procedure gave an accurate determination of the peak strength envelope of the reference material from a single specimen. The peak strength envelope derived by this method closely approximates that derived from single state tests, the average experimental discrepancy being of the order of ±5%. This indicates that the volumetric strain/axial strain relationship can be used to accurately predict the onset of instability in the specimen, allowing the test to be stopped, stabilised and restarted at a higher level of confining stress.

The modified procedure as outlined does not conform to the ISRM standard. In the standard procedure, σ_1 is kept at the previous maximum value while σ_3 is increased to restore stability (Figure 1). In the modified testing procedure, the specimen is stable at the end of each stage. The specimen is allowed to recover part of its elastic deformation due to the relaxation of stresses to the hydrostatic level (Figure 5). It is considered that this modified testing procedure more accurately reproduces single state test conditions than the ISRM standard (type II) procedure at each subsequent stage of testing.

In the future, it is hoped that the discrepancy currently observed between the peak strength envelopes determined by the two methods described above can be reduced by using servo-control of the confining stress with direct measurement of specimen volume change as the feedback parameter.

ACKNOWLEDGEMENTS

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